ECAL group

LEP Energy Group/96-05
22 July, 1996

LEP Energy Calibration in 1993, 1994 and 1995

The working group on LEP energy

Abstract

The preliminary determination of the collision energies in the 1995 LEP scan is presented. The discovery of an energy rise during a fill is described. It is discussed how this new effect is accommodated in the modelling of the mean beam energy in 1995 and the implications for the 1993 and 1994 energies. The analysis of the interaction point specific corrections to the collision energies in 1995 is summarised; these arise from the RF system and from opposite sign vertical dispersion induced by the bunch train mode of LEP operation. Preliminary errors on the collision energies for the 1993, 1994 and 1995 datasets are given. For 1993 these supersede the previously published values.

Finally, a new evaluation of the LEP beam energy spread is presented. This significantly improves the precision with which this parameter is known with respect to previous analyses.

1 Overview

In 1993 and 1995 LEP performed a scan of the Z^0 resonance to determine the parameters M_Z and Γ_Z. An accurate knowledge of the collision energy is crucial to benefit from the available statistics. The calibration of the energy in 1993 is described in [1]. In 1994, all LEP running was at the Z^0 peak. The 1994 preliminary energy calibration used until now followed the same method adopted for 1993 [2].

This note presents the present status of the energy determination for the 1995 scan. From study of the 1995 data it has been learnt that the LEP beam energy exhibits a significant rise during the course of a fill. The evidence for the rise is discussed, and the inclusion of this term in the analysis described.

As a result of the discovery of this effect, the 1993 and 1994 energies must be revised. It is explained how the parameterisation of 1995 can be applied to the earlier years, and what data exist in these years to support this treatment.

To obtain the collision energies at each experiment requires additional interaction point (IP) specific corrections. These corrections in 1995 have two components. One is the status of the LEP RF system, the other is the effect of opposite sign vertical dispersion induced by the bunch train operation. Both analyses are discussed.

The systematic errors on the collision energies are given, together with their correlation between experiments and energy points.

Finally, the knowledge of the beam energy spread in 1993, 1994 and 1995 is summarised. This is an important systematic error on Γ_Z. An improved understanding of the relationship between the coherent and incoherent synchrotron tune has enabled the uncertainty on the energy spread to be reduced by a factor of four with respect to the previous determination.

All numbers in this document are preliminary.

2 1995 Scan

As in 1993, the 1995 Z^0 scan was made at three energy points, peak ('P') and two points approximately 1760 MeV either side of peak ('P+2' and 'P–2'). The offpeak integrated luminosity was $\sim 18\,\mathrm{pb}^{-1}$, delivered over 52 fills and evenly distributed between the two energy points [1].

Attempts were made to calibrate essentially every offpeak fill after physics collisions, at end of fill ('EOF'), using the technique of **resonant depolarisation** [3]. This was realised for 14 fills at P+2, and 12 fills at P–2. These calibrated fills represent $\approx 70\%$ of the offpeak luminosity, to be compared with the figure of $\approx 40\%$ achieved in 1993.

The calibrations were made by depolarisation of the electron beam. A dedicated experiment established that the positron beam energy is identical, within an uncertainty of 0.25 MeV.

Of these fills with EOF calibrations, 4 fills were also calibrated before physics collisions, at beginning of fill ('BOF'). Such BOF/EOF calibrations had not been performed in 1993; they were scheduled in 1995 to monitor any energy variation during a fill. In addition to these physics fills, 2 machine developments had an extended series of polarisation measurements over the fill, giving 6 BOF/EOF calibration experiments in total.

[1] The scan is considered to encompass all fills between 2852 and 3042, inclusive.

In 1993, the magnetic field of LEP was monitored with an NMR probe mounted in the reference magnet. The reference magnet is connected in series with the LEP dipoles, but mounted outside the tunnel. For the 1995 scan two additional NMRs were installed within the tunnel itself, mounted in actual LEP dipoles. These are known as 'NMR4' and 'NMR8', on account of their positions around the ring. This new instrumentation provided direct measurements of the bending field, albeit at specific locations.

The results of the BOF/EOF calibration experiments, and the behaviour of the new NMRs, are discussed in section 3.

Two innovations in LEP operation distinguished the 1995 running from that of previous years, and have relevance for the energy determination.

- **Commissioning of superconducting RF cavities**

  In preparation for upgrading the LEP energies, superconducting RF cavities were commissioned throughout the 1995 running period. The RF during the scan was a varying mixture of conventional copper and new superconducting cavities. This hybrid system must be understood to arrive at interaction point specific RF corrections to the centre-of-mass energies, as is described in section 5.

- **Bunch trains superseeded Pretzel running**

  During the scan, the electrons (and positrons) were distributed in four trains of three wagons, each wagon separated by 247 ns. This is to be contrasted with the eight equally spaced bunches of LEP operation in the Pretzel mode of 1993 and 1994. In bunch train operation electrostatic deflections ('bumps') are applied either side of the IP to avoid parasitic collisions between wagons. These bumps induce opposite sign vertical energy dispersion for the two beams, which can lead to offsets in the centre-of-mass energy. This issue is addressed in section 6.

  The interaction between the bunch trains and the RF cavities must also be considered.

Finally, attempts were made to keep the machine conditions stable, and as similar as possible for physics and calibration at the two offpeak points. In contrast to 1993, the magnet cooling was regulated to keep the variation of the core temperatures to a minimum. Also, the current in the QFQD compensation loop was held constant throughout the entire scan.

3 Determination of the mean energies of LEP in 1995

The resonant depolarisation calibrations provide accurate instantaneous measurements of the mean beam energy. A priori, these calibrated fills are unbiased estimators of the entire set of fills and thus of the mean value of each energy point. However, the calibrations show a significant RMS spread (~ 5 MeV per beam at each energy point in 1995). This scatter results from the genuine variation in the LEP energy over time, a variation driven by effects discussed in [1], such as magnet temperatures, tides and geological deformations of the LEP ring. When understood, these effects can be described in a model, and the spread of the calibrated energies largely reproduced. Any residual scatter of the calibrations with respect to this model arises from unknown factors in the fill to fill energy variation, and can be used to assign an error to the knowledge of the mean energies. This procedure is fully described in [1].

Most of the depolarisation measurements in 1995 physics fills, and all in 1993, were EOF calibrations. The comparison of model with these measurements provides a direct measure of the understanding of the fill to fill energy variation, but is rather insensitive to any change during a fill itself. Knowledge of this short term variation was gained through analysis of the BOF/EOF experiments and NMR measurements in 1995. The model was then extended to include this new component.

3.1 Energy rise in a fill and related observations

Both the 6 BOF/EOF experiments and the tunnel NMRs indicated that, rather than remaining constant, on average the energy of LEP rises throughout a fill. This rise occurs independently of any variation induced by other causes of energy change, such as temperature.

The BOF/EOF calibration fills exhibited a rise in the beam energy. The mean rise between first and last depolarisation was 3.9 MeV. This mean has a significant RMS scatter of 2.6 MeV. Some of this scatter can be attributed to the variation in the length of the experiments (between 6 and 20 hours), but the apparent energy change was not identical in all fills.

The NMRs recorded an increase in the dipole field over the fill. Assuming that this can be related to the beam energy, the field change is equivalent to a rise of a few MeV over a typical fill. The field change observed was not necessarily the same in NMR4 and NMR8; the relative rises in both varied from fill to fill, as did the absolute size of the increase. Averaged over many fills however, the behaviour is distinctive, as can be seen in figure 1(a), which shows the integrated rise expressed in MeV as a function of time in fill. The rise is at first steep, but after ~ 10 hours saturates. The differential rise per hour as a function of time in fill is shown in figure 1(b).

In addition to revealing a field rise, the NMRs displayed significant short term noise. Occasionally, jumps also occurred, with sudden steps observed in the field. These phenomena were found to be strongly anti-correlated between NMR4 and NMR8; this is shown in figure 1(d). Constructing the pseudo-device NMR48, where

$$\mathrm{NMR48} \equiv \frac{5}{8}\mathrm{NMR4} + \frac{3}{8}\mathrm{NMR8}, \tag{1}$$

yields an 'average NMR' sampling the field at both positions around the ring, eliminating almost completely the anti-correlated noise.

The noise in the NMRs was found to have an unexpected dependence on time of day. Much quieter behaviour was observed between midnight and about 5:00, at which point the noise resumed. The field rise was studied as a function of time of day: the rise was found to be much smaller in the 'quiet period' than in the remainder of the day. The rise as a function of time of day is seen in figure 1(c).

Eventually the NMR noise was correlated with a current flowing on the LEP beam pipe. This current fluctuates in amplitude with time and position around the ring, with typical magnitude of ~ 1 A. It enters close to the injection lines at IP1 and flows in both directions around LEP, exiting near the Versoix river at IP6. The current's behaviour in the regions of NMR4 and NMR8 is consistent with the anti-correlated noise seen in these devices. Measurements of the current amplitude supports the choice of coefficients in expression 1, defining NMR48. Furthermore, the current activity is highest during the day, but at a low level in the early morning.

The current arises from electrical trains passing on the Geneva-La Plaine line. A fraction of the current powering the train leaks to earth when returning to the generator station. This current passes through the earth and on to the LEP beam pipe. The quiet period between midnight and 5:00 is a consequence of there being no trains in the area at this time. A dedicated experiment monitoring the voltage between the train rails and earth recorded a signal clearly correlated with the variations in the beampipe current and the NMR field.

It is believed that the current flowing on the beampipe perturbs the equilibrium of the magnetic domain of the LEP dipoles. At the start of fill these dipoles are not at the top of their hysterisis cycle. The excitation of the beampipe current induces a rise in field. The dipole will eventually reach maximum field. This is presumably the saturation apparent in figure 1(a). It is possible that other sources, in addition to the beampipe current, contribute to the dipole stimulation.

Further discussion of these phenomena can be found in [4] and [5].

3.2 Modelling the energy rise in the fill

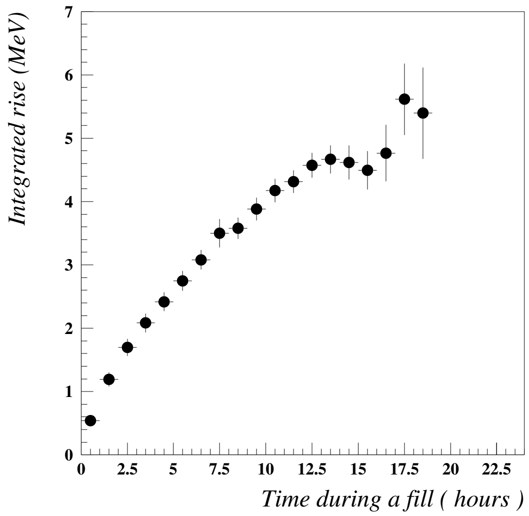
The fill energy rise must be included in the model of the LEP dipole field. This can be done through use of the NMR data [6], or from use of the BOF/EOF depolarisation data [7]. For the preliminary energy values released for the 1996 summer conferences the former approach was adopted. A comparison with the alternative method provided a cross check which was considered in the systematic error assignment.

3.2.1 The NMR average behaviour model

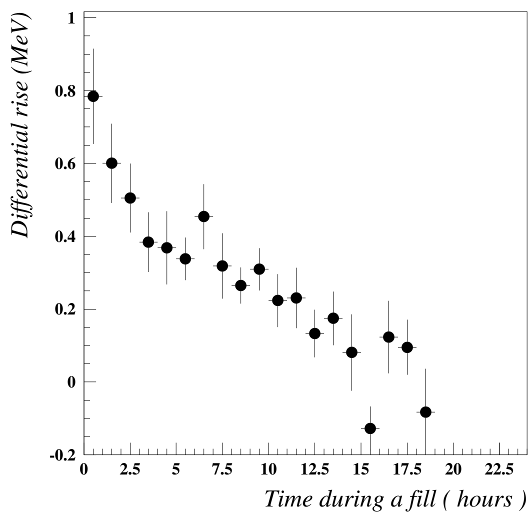
The NMR48 data over the entire scan were histogrammed as a function of time in fill, t_{fill}, and time of day, t_{day}. The resulting distributions were then inspected to compute corrections to the energy in fills at specific values of these two variables. The distributions were broadly similar at P$-$2 and P+2 and thus all the data were taken together.

This use of the average behaviour of NMR48 was preferred to making a direct correction from the synchronous data themselves to permit a consistent treatment of the 1993, 1994 and 1995 data. In 1993 and 1994 there were no NMRs in the tunnel. Reference to the average behaviour in 1995 established a procedure which could be applied without technical difficulty to the previous years.

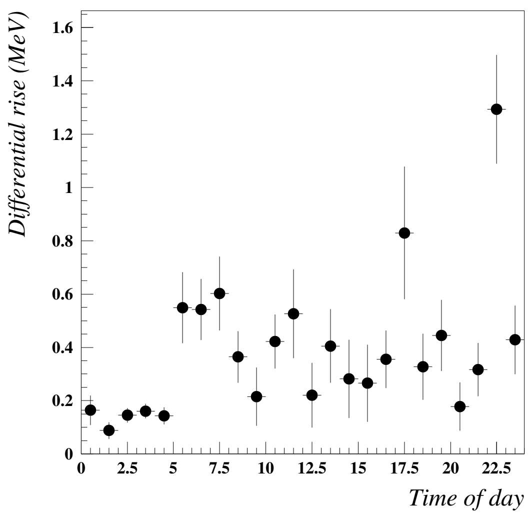
An additional consideration is introduced by the presence of **bending modulations**. A bending modulation is a rapid cycling of the dipole current, usually applied at start of fill, with the aim of raising the magnets to the top of their hysterisis loop and increasing their stability. This practice was instigated part way through the scan. As expected, the rate of NMR rise after a bending modulation is on average lower than the rate of rise before. The data were divided into the sets of before (or without) and after bending modulations. In the model, the appropriate set was chosen for the rise term depending on the conditions of the fill under consideration. Usually an instantaneous jump was observed by the NMRs at the time of a bending modulation. This was parameterised in the model by a step of 2.5 ± 1.0 MeV in the beam energy.



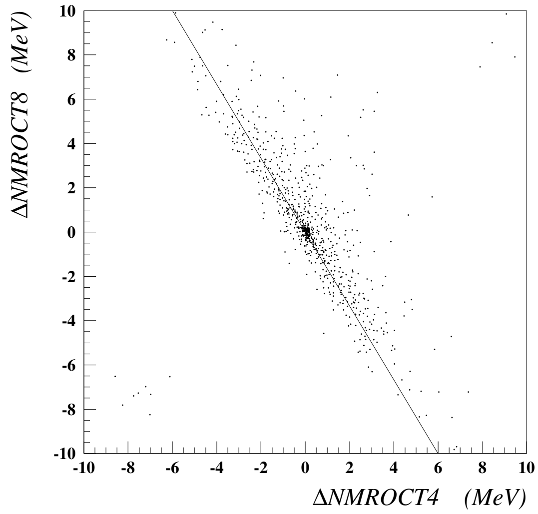
(a) Integrated rise in fill.



(b) Differential rise in fill.



(c) Differential rise in day.



(d) Noise in NMR4 vs NMR8. The line has the parameters of expression 1.

Figure 1: *NMR behaviour in 1995. All effective energies are per beam.*

Two problems occur in the interpretation of the NMR data. Firstly, the field changes in NMR48 must be corrected for the changes coming from the temperature variation of the two dipoles. That is, the temperature coefficient of the NMR dipoles must be understood. Secondly, one must assume that the beam energy exhibits the same dependence with $t_{\rm fill}$ and $t_{\rm day}$ in magnitude and form as is observed in the NMRs.

The temperature coefficient of the pseudo-dipole corresponding to NMR48 was determined from the data of the scan. Assuming that the temperature of this device can be constructed as in expression 1, the change in magnet core temperature, ΔT_{48}, was fitted to the change in energy, ΔE_{48}, and thus the temperature coefficient C_T^{48} extracted.

Various factors complicated this analysis:

- The core temperatures of the LEP dipoles were kept as stable as possible throughout the scan. Most fills showed variations of less than 0.5° C. This is not large compared to the intrinsic precision of the temperature probes, which was 0.1°.
- The noise and jumps seen in the NMRs was a significant background to any field variation arising from temperature.
- Any measurements of C_T^{48} over long time intervals ($\sim$ 1 hour), were distorted by non-linear effects arising from, for instance the train currents themselves.

These systematic problems prevented a precise determination of C_T^{48}. However, the measurements were consistent with the following value:

$$C_T^{48} \;=\; 0.25 \pm 0.25 \times 10^{-4}/^{\circ}\mathrm{C}. \tag{2}$$

Here C_T^{48} is the fractional change in energy with magnet core temperature.

It is interesting that the value of this coefficient is significantly smaller than that conventionally used for the LEP ring as a whole, $C_T^{\rm ring}$. In [1] the latter was taken to be $C_T^{\rm ring} \;=\; 1.00 \pm 0.25 \times 10^{-4}/^{\circ}\mathrm{C}$, following earlier measurements [3]. This difference is not yet understood. A dedicated testbench has been established to study in detail the thermal behaviour of a LEP dipole. Results from these tests will be included in the final publication [8].

As the modelling of the fill to fill energy variation can be tested through comparison with the EOF calibrations, so can the modelling of the fill rise term be compared with the 6 BOF/EOF experiments in 1995. This comparison is shown in figure 2. In this figure the change between the first and last depolarisation measurements has been corrected for the quadrupole field effects of tide and variations in the horizontal orbit, to leave the residual rise in the dipole field component. Observe that the observed rise has a large scatter, but the comparison with the model gives a narrower distribution and one centred on zero.

3.2.2 The depolarisation data model

An alternative method to using the NMR data is to fit a functional form to fills with more than one depolarisation measurement, and to use this function to determine the energy rise with time. The advantages of this approach is that it is independent of the questions of whether the NMRs are represenative of the beam energy and what is the NMR48 dipole temperature coefficient. However the data sample available is more limited.

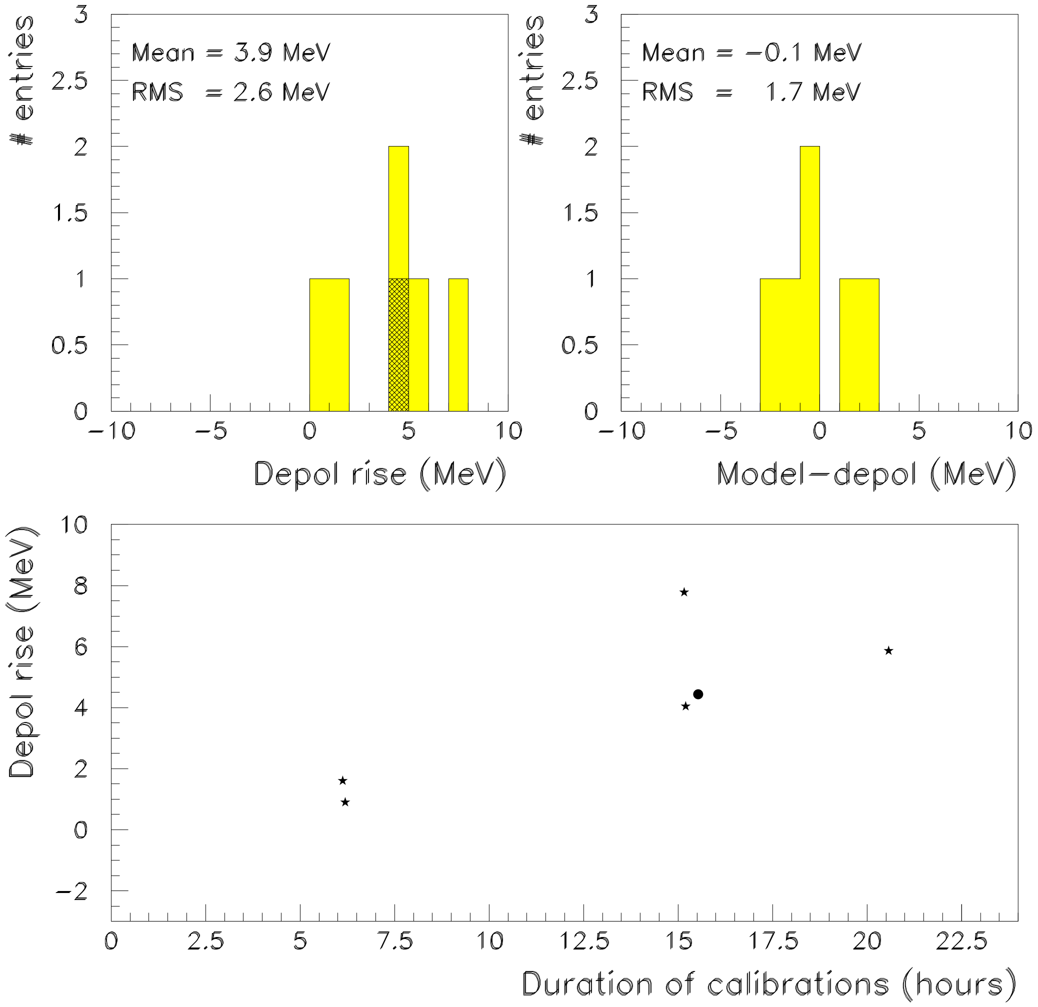


Figure 2: *Long calibration experiments in 1995. The fills considered are 2929, 3022, 3029, 3030, 3036 and 3064. Shown is the distribution of the dipole change seen between the first and last depolarisation measurement (top left); the distribution of the depolarisation dipole change minus the change predicted by the model (top right); the depolarisation change against interval between first and last measurement (bottom). The fill indicated by dark hatching in the top left plot and by a circle in the bottom plot experienced a bending modulation between calibrations, which induced an energy jump of* ~ 1 MeV. *In every fill the first calibration occured within 5 hours of the magnets being ramped to nominal field. All changes are given in* MeV *per beam.*

A fit was made to the BOF/EOF depolarisation measurements of 1995. As well as these fills, several long term calibration machine developments from 1993 were included in the sample (see section 4 for discussion of these experiments). The fit involved a term representing the $t_{\rm day}$ dependence and a term representing the $t_{\rm fill}$ dependence. The mean core temperature of all the monitored LEP dipoles was an additional input variable, and the ring temperature coefficient, $C_T^{\rm ring}$, left as a free parameter. The results as determined from P–2 and P+2 fills were consistent, and thus the full set was used to determine a common rise function independent of energy point.

Within the limited statistics available, the depolarisation data did not suggest as strongly as the NMR data that the energy rise saturates after $\sim$ 12 hours of fill, and the fitted model reflected this. However, when applied to the 1995 data the two models agreed to within 0.5 MeV in the collision energies at P+2 and P–2.

3.3 Other aspects of the 1995 analysis

Aside from the fill rise term, the 1995 model was very similar to that developed for the 1993 scan. Note that the constant value of the QFQD current and the relative stability of the dipole core temperatures reduced the number of important components in the analysis.

A new consideration concerned the effect of correctors. These are small dipole magnets installed in LEP to compensate for the misalignment of the quadrupoles around the ideal orbit and to correct the beam orbit in both planes. Simulations show that the horizontal corrector magnets can affect the beam energy signifiantly through a change in path length if the fields add up coherently. The main effect of the corrector is to change the path length of the beam proportionally to the product of its deflection angle and the horizontal dispersion. Since the orbit length is fixed by the RF frequency, the change in path induced by a corrector forces the beam to change its radial position in the quadrupoles. The additional fields seen by the beam in the quadrupoles lead then to a change in energy. This effect is implictly included in the model by the horizontal beam position measurements in the arcs made with the BOM system. However, differences in corrector settings between calibration and physics modes must be properly taken into account and can potentially lead to a bias on the beam energy.

A correction was computed from the measured differences of corrector settings in physics and calibration. It is important to note that the effect of the horizontal correctors has not been observed directly up to now. A controlled experiment will be scheduled during the present LEP run. Thus in calculating the central values of the energies, only half of the predicted effect was applied, and half taken as error.

4 Revision of the 1993 and 1994 LEP energies

4.1 Energy rise in fill

The modelling of the energy rise in a fill must be included in the 1993 and 1994 analyses, as the effect was almost certainly present in these years also. The description of the rise for these data must rely strongly on the observations made in 1995. However there exist calibration experiments in these years, which, when interpreted in the light of the

1995 experience, gives confidence that the rise term was indeed present and of similar magnitude as observed in the later scan.

Most significant of the experiments was a machine development of almost 24 hours, fill 1772, in which a long series of depolarisation measurements were made with the aim of determining the ring temperature coefficient, C_T^{ring}. Between the first and last measurements a change in energy of 8 MeV was seen for a temperature variation of $\sim 0.7°$. This large excursion implied a value of C_T^{ring} in excess of any expectation, and thus the experiment was not understood. Reinterpreted with hindsight, the data are consistent with a beampipe current driven rise of the same rate as in 1995, and a temperature related component with $C_T^{\mathrm{ring}} \approx 10^{-4}/°\mathrm{C}$, in agreement with independent determinations [3].

In 6 further fills, calibrations spanning intervals of 2 to 11 hours were made. On average these fills exhibited an energy rise which was similar to that predicted by the 1995 model. However, most of these calibrations were made when the magnets had been at nominal field for many hours; then the rate of rise is expected to be small. The remainder of the calibration periods were short. Thus the mean rise observed over the calibrations, though in agreement with the model, is smaller than that of the BOF/EOF fills in 1995 and the statistical power of the data in constraining the uncertainty in the rise term is not as strong.

The rise seen by the depolarisation and the comparison of this rise with the model is shown in figure 3. The rise seen by the depolarisation has been corrected for quadrupole effects, as described in section 3.2. In the distribution of depolarisation rise against interval between first and last calibration, those fills where the first measurement occured after more than 10 hours are indicated by open squares.

In modelling the rise term in 1993, both the NMR based approach and the depolarisation data procedure were applied. The agreement in the obtained mean energy between the two methods was less good than in 1995. In particular a difference of 1.4 MeV in centre-of-mass was found at P+2. This was understood to arise from the continual energy rise predicted by the depolarisation model late in the fill, to be contrasted with the saturation of the NMR based model. In 1993 the P+2 EOF calibrations took place, on average, 4 hours later into the fill than the P–2 EOF calibrations. This asymmetry convoluted with the variation between the models is responsible for the difference in mean energies. This model dependence was considered in the assignment of the preliminary systematic errors (see section 7). Further analysis of the available data and future measurements of the energy rise late in fills may improve the understanding of this issue.

4.2 Correctors

As for 1995, it is unknown whether the difference in corrector settings between physics and calibration operation implies a change in dipole field which should be accounted for in the normalisation of the model to the calibration points. The effect was ignored in determining the central values, but an error assigned. This error was not considered in [1].

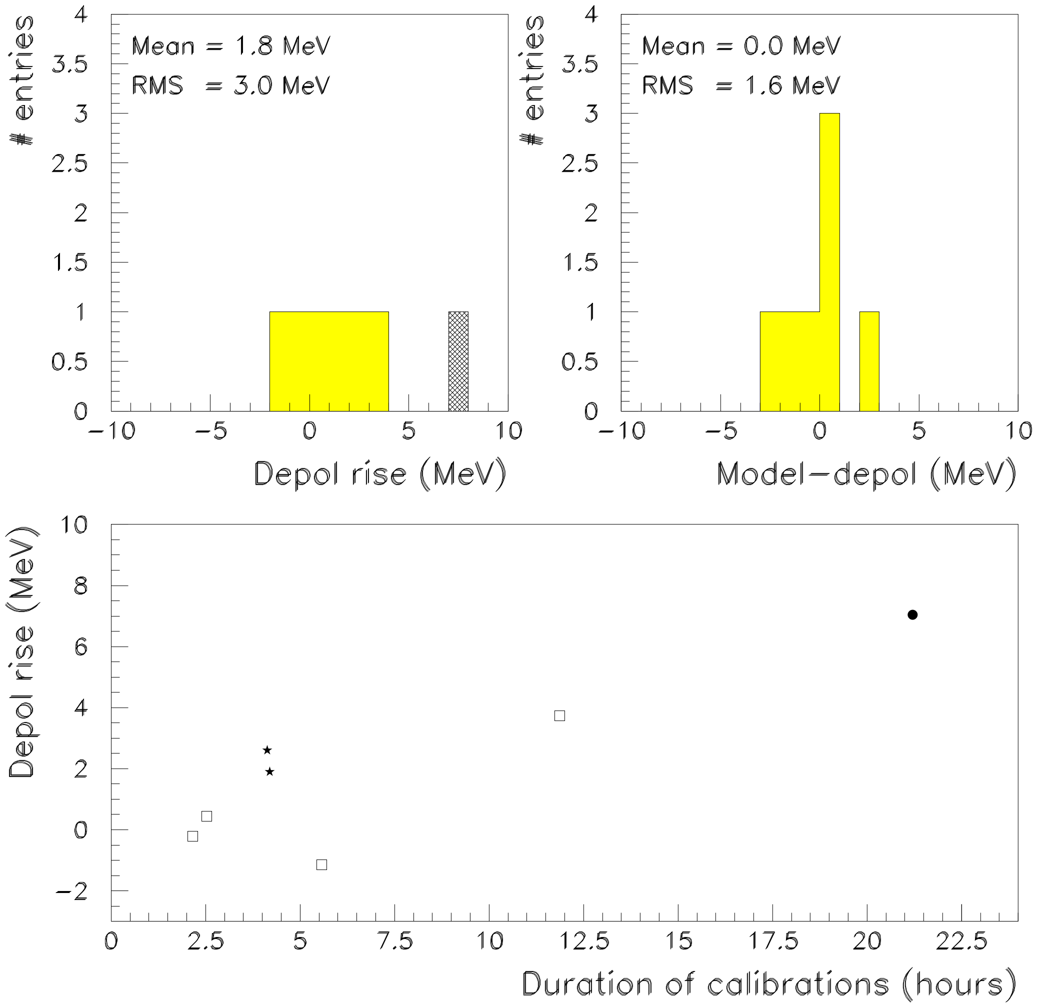


Figure 3: *Long calibration experiments in 1993. The fills considered are 1636, 1734, 1772, 1811, 1849, 1888 and 1892. Shown is the distribution of the change seen between the first and last depolarisation measurement (top left); the distribution of the depolarisation change minus the change predicted by the model (top right); the depolarisation change against interval between first and last measurement (bottom). The fill indicated by hatching in the top left plot and by a circle in the bottom plot is 1772, which experienced a temperature variation significantly larger than that of normal physics running. In the last plot the open squares indicate those fills where the first calibration occured more than 10 hours after the magnets reached nominal field. All changes are given in* MeV *per beam.*

5 Collision energy corrections from the RF System in 1995

Here is described the analysis of the effect of the RF system on the centre-of-mass energy. More details on this analysis can be found in [9].

5.1 Determining the corrections

The beam energy loss due to synchrotron radiation is compensated by acceleration provided by RF cavities placed at IP2 and IP6, which are at diametrically opposite points on the LEP ring. Due to misalignments of the copper (CU) RF system, the beam energies are shifted locally at IP2 and IP6. Hence corrections to the average beam energy must be applied to obtain the proper value of the centre-of-mass energy E_{CM}. Other geometrical effects, such as a non-zero path length difference between the path IP2-IP4-IP6 and IP2-IP8-IP6 (defined as $\Delta\ell_{26}$), can result in non-zero corrections at points 4 and 8 as well.

As in past years [1], the modelling of the corrections is carried out by the iterative calculation of the stable RF phase angle ϕ_s which proceeds by setting the total energy gain of the beams as they travel around the machine equal to all of the known energy losses. In the past, the measured value of the synchrotron tune Q_s was compared to the value calculated from the model, and modifications were made to the model in order to achieve better agreement between the two Q_s values. In addition, longitudinal shifts of the collision point in the IPs could also be traced to changes in the RF configuration, and hence could be predicted from the model. A comparison of these predicted and measured shifts provides another way of cross-checking the model's validity.

The 1995 RF model includes several updates specific to the new running conditions experienced during the 1995 scan. First, the introduction of the bunch train running has necessitated the independent simulation of ϕ_s for each wagon in the bunch trains which takes into account the details of interwagon spacing and the different wagon positions on the RF voltage envelope. Second, the first series of superconducting (SC) cavities which are needed for LEP2 running, including their complete set of alignment and voltage calibration constants, has been added. The use of a small number of high-gradient cavities to provide the necessary RF power requires a third component to be added to the model, namely a means of describing the interaction of the beams with those cavities that are unused. A so-called "weak" beam loading model, where the wagons deposit energy in the unused cavities equivalent to the measured peak induced voltage but do not interact with the stored energy, has been implemented. The fourth addition is a new diagnostic tool, called R_{BOM}, which combines the measured size of the electron-positron difference orbit Δ^{+-} on both sides of IP2 and IP6 into a ratio which is sensitive to the phasing of both individual RF units at each IP and the relative phase of the RF between IP2 and IP6. The definition of R_{BOM} is:

$$R_{BOM} = \frac{|\Delta^{+-}_{IP2\ Left}| + |\Delta^{+-}_{IP2\ Right}|}{|\Delta^{+-}_{IP6\ Left}| + |\Delta^{+-}_{IP6\ Right}|} \,. \tag{3}$$

Based on the modelled energy loss and the known lattice dispersion, this quantity can also be calculated in the RF model. Comparison with the measured values places powerful constraints on whether or not the RF phases of the cavities input to the model are correct.

The calculations of the RF corrections utilise a database of patched and corrected input values where any necessary information that was not available from the variety of logging sources has been interpolated. Approximately one-third of the records used contain at least one interpolated value. A systematic error based on the quality of this data is included in the final set of errors.

After the tuning of the RF model, which required the input of time-dependent mis-phasing and voltage calibration errors, the difference between the measured and calculated values of Q_s for each RF record has a mean of –0.00034 and an RMS of 0.0008. Note that this agreement is obtained with an overall scaling of 2% applied to the values of the measured voltages. The corresponding values from the 1993 scan were 0.0001 and 0.0004. The mean of the distribution $R_{BOM}(\text{calc})/R_{BOM}(\text{meas})$ is 1.009, with an RMS of 0.077. Note that the RMS of the Q_s difference is approximately twice as large in 1995 than it was in 1993; this is due to the instability of the RF configuration during the scan. An additional error on the voltage scale was added to account for this larger variation. The average corrections for the offpeak points during the 1995 scan are shown in Table 1. Table 2 gives the average wagon-specific corrections for each IP. Since the CU RF was on at IP 2 most of the time, IP 2 sees the largest wagon-to-wagon variation due to the natural spread in wagon energies caused by their relative positions on the voltage "envelope" of the CU cavities. As these variations are small, no wagon-to-wagon distinction was made in the preliminary energy determination; rather the average values were used.

LEP IP	ΔE_{CM} P–2	ΔE_{CM} P+2
2	14.70	14.69
4	0.81	1.29
6	4.31	4.54
8	–0.88	–1.38

Table 1: *The corrections (in MeV) to E_{CM} for each LEP IP and each offpeak point for the 1995 scan RF model.*

LEP IP	$\Delta E_{CM}(a)$	$\Delta E_{CM}(b)$	$\Delta E_{CM}(c)$
2	14.30	14.72	15.07
4	1.08	1.06	1.05
6	4.30	4.45	4.56
8	–1.16	–1.15	–1.13

Table 2: *The average corrections (in MeV) to E_{CM} for each LEP IP for each wagon in the 1995 scan RF model.*

5.2 Evaluation of Errors for the RF Corrections

The constituent errors on the preliminary 1995 analysis are discussed below. Note that they can be divided into those common to and correlated between all experiments and those affecting specific IPs or pairs of IPs. The errors are summarized in Table 3.

5.2.1 Comparison of data and model in Q_s

The difference between the Q_s measured for electrons and positrons is 0.00004, which is consistent with there being no large residual phase errors on the CU cavities. This difference in the RF model output, however, is 0.0001. An overall uncertainty of 0.2 MeV was added for all experiments to account for possible differences in energy due to this effect. This was taken as 50% correlated between P–2 and P+2, and anticorrelated between IP4 and IP8.

As mentioned above, the voltages obtained from the database were scaled upwards by an overall factor of 2% in order to obtain good agreement between the measured and calculated Q_s. In the 1993 analysis, half of the normalisation factor was taken as the error. In 1995, however, the RMS of the difference between the measured and calculated Q_s is nearly twice as large. This is due mainly to the instability of the RF configuration during the scan. To cover the full spread of possibilities in the voltage description, the full normalisation correction was taken as the error. This resulted in errors of 0.4 and 0.1 MeV at IP2 and IP6, respectively, and much smaller errors at IP4 and IP8. As this sets the overall scale, it is 100% correlated between P–2 and P+2, and correlated between IP2 and IP6.

A comparison of the RF model and the data has been carried out for the fills at P–2, P, and P+2 separately. The difference in the agreement between measured and calculated Q_s at P–2 and P+2 is 0.00007, which is negligible in terms of a possible energy difference. For fills on the peak, the agreement between calculated and measured Q_s, –0.00049 is slightly larger than the fills offpeak. This discrepancy corresponds to an additional ~ 0.2 MeV error on the peak energies, which is entirely negligible.

5.2.2 Comparison of data and model in vertex position

Checking the predictions of the RF model against the experimental data for the position of the average interaction point and the individual wagon collision points measured along the beam axis has revealed several deficiencies in the model parameters. As yet, the RF model is incapable of reproducing either the extremes of the motions of the average vertex towards for a small period at the end of the scan or the large spread in wagon collision points.

The average motion could be explained by several geometrical effects, all of which, however, have been ruled out by measurement. A constraint on the possible size of this effect can be obtained by postulating that something external is causing the extra vertex motion, and to calculate the effect of having one of the beams sit at a slightly different ϕ_s. Using the stable phases calculated from the RF model for the fills in question, the energy shifts are 0.7 MeV at P–2 and 0.8 MeV at P+2 for all IPs. Using the OPAL integrated luminosity, these fills represent 1.6 pb^{-1} at P–2 and 1.0 pb^{-1} at P+2, so the overall effect on the entire scan would be to induce net shifts of 0.14 MeV and 0.1 MeV at P–2 and P+2, respectively. For the time being, these were taken as systematic errors due to this residual discrepancy. This error is common to all experiments, and was conservatively assumed to be 50% correlated between P–2 and P+2.

A summary of the model/data agreement on the position of the wagon vertices can be seen in Figure 4. Two striking features of the data are evident:

- The wagons do not sit "symmetrically" on the RF envelope. Wagon b is on average closer to c than to a, most obviously so for the beginning portion of the scan.
- The spacing in z between a and c is much larger that that predicted by the RF model.

These two features imply that neither the average stable phase for each wagon nor the stable phase differences between the two beams are being properly modelled. There is, however, one external constraint on possible energy variations: the average difference in the energy of wagon a and c measured by resonant depolarisation at IP1 is –0.1 MeV, with an RMS of 0.3 MeV. The fact that the energy difference between the wagons has been measured places a constraint on the maximum possible effects at IP4 and IP8. Taking the RMS as the full allowed range of the $a - c$ energy difference, this translates into a maximum possible difference in E_{CM} of 0.8 MeV between wagons a and c. Since only average energies are given, this would amount to a 0.4 MeV uncertainty at IP4 and IP8, assuming b sits on average half way between a and c. This error was taken as 50% correlated between P–2 and P+2, and correlated between experiments. At IP2 and IP6, estimating the possible energy shifts is more difficult, since it is possible that large effects could be induced locally by the RF which would be invisible outside of that specific IP. Assuming that the RF system cannot be responsible for the wagon shifts (*i.e.*, some external constraint forces them to sit at different stable phase angles ϕ_s), the effects of the longitudinal shifts were simulated in the following manner. For each RF record in the dataset, the difference in z position between the RF model prediction and the LEP average beam position was calculated for each wagon. This was converted into a difference in stable phase angle $\Delta\phi_s$, which was then input back into the RF model as a constraint on the simulation. The results of this simulation showed differences in E_{CM} of ~ 0.3 MeV at IP4 and IP8, which were certainly consistent with the constraints derived above. At IP2 and IP6, shifts of up to 0.6 MeV were seen. The largest variation (which occurs at IP2) was taken as the error in this case, with the same correlation as the error at IP4 and IP8.

5.2.3 Comparison of data and model in R_{BOM}

The quantity R_{BOM} provides a rather stringent constraint on the possible phase errors between IP2 and IP6 and within the RF at each IP. To estimate the quality of the RF model's description of the phasing of the RF, the error for the measurement of each of the quantities Δ^{+-} in equation 3 was taken to be 20μm and the corresponding error on R_{BOM} was calculated for each entry. The distribution $[R_{BOM}(\text{calc}) - R_{BOM}(\text{meas})]/\sigma(R_{BOM})$ has a width of approximately 2.1, which implies that R_{BOM} and hence the phasing of the machine is only tuned to a level of approximately twice the available resolution of 0.03. The implications of this were studied by shifting the relative RF phase between IP2 and IP6 in a way to move R_{BOM} by 0.06 on average. The largest effect was caused by changing the phases on only the CU cavities, and this was taken as the potential error due to misphasing. The size of the effect was 0.1 MeV at IP2, 0.04 MeV at IP6, and negligible at IP4 and IP8, and was correlated between IP2 and IP6. It was taken as 50% correlated between energy points to be conservative.

5.2.4 Effects of record interpolation

The errors from interpolating to recover the missing values were estimated by comparing the agreement in the measured and calculated Q_s values for all those records which have had to be extrapolated to fill in gaps in the database. The difference in agreement of Q_s is $-.0006$, which results in an energy shift of ~ 0.3 MeV. Taking one-third of this (one-third of records are affected) gave another overall uncertainty of 0.1 MeV to be added. This error is common to all experiments, and was assigned a 50% correlation between energy points.

5.2.5 Other errors

In addition to the errors arising from the procedures discussed above, there are errors due to uncertainties on the following quantities:

- **RF cavity positions**

  For 1995, the effects of the cavity misalignments were estimated for the CU and SC cavities independently, and added to obtain the total error. The uncertainty on the CU alignment was taken to be ± 1 mm, where the most conservative estimate of the effect was to assume that the total uncertainty on the difference in cavity positions is 2 mm, moving the cavities coherently towards or away from the IP to calculate the effect. This led to a shift of 0.6 MeV at IP2 and 0.2 MeV at IP6. Recent measurements have suggested that the SC cavity alignments could be uncertain by 2.5 mm. With the largest possible relative displacement of the cavities taken in the same manner, this led to a shift of 0.2 MeV at IP2 and 1.7 MeV at IP6. The total error for these two sources was then 0.8 MeV at IP2 and 1.9 MeV at IP6, uncorrelated between the two. As the source of this error is geometrical, it was taken as 100% correlated between energy points.

- **Lengths of the LEP arcs**

  This was taken as 0.1 MeV (correlated) in IP2 and IP6, as in 1993. A 100% correlation between energy points was assigned.

- **Momentum compaction factor α_c**

  This was taken as 0.1 MeV (correlated) in IP2 and IP6, as in 1993. A 100% correlation between energy points was assigned.

6 Collision energy corrections from dispersion in 1995

Here is described the analysis of the effect of dispersion on the centre-of-mass energy. More details on this analysis can be found in [10].

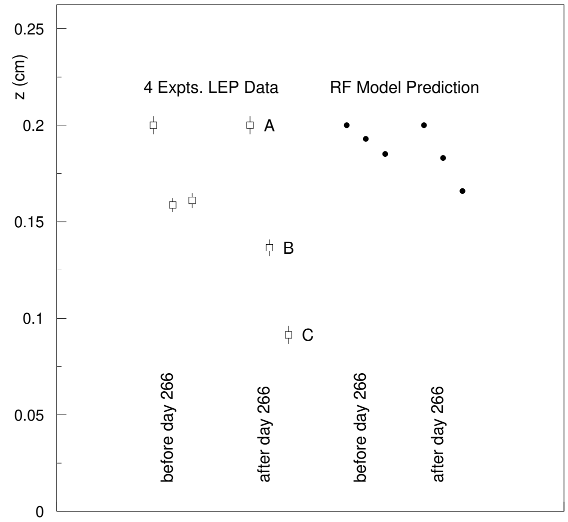


Figure 4: *A comparison of the measurements and predictions of the average z position of the collision points of the three wagons, labelled "A", "B", and "C". The predictions of the RF model are also shown for the default "weak" beamloading model. The data are broken into two periods during the scan, one before the SC RF was dominant (before day 266) and one after, where the day is counted from 1 January, 1995.*

6.1 Introduction

The 1995 energy scan required the control of a new effect associatated with the bunch train bumps. These bumps generate opposite sign vertical dispersion at the interaction points of LEP. If the beams collide with a collision offset then the centre-of-mass energy is shifted from the nominal by an amount ΔE_{CM} [11]:

$$E_{CM} = E(e^+) + E(e^-) + \Delta E_{CM} \tag{4}$$

$$\Delta E_{CM} = -\frac{1}{2} \cdot \frac{\delta y}{\sigma_y^2} \cdot \frac{\sigma_E^2}{E} \cdot \Delta D_y^* \tag{5}$$

where δy, the collision offset, is the distance between the centre of the positron bunch and the electron bunch in collision at the IP, σ_y the individual beam size, ΔD_y^* the difference in the vertical dispersion $(D^*_{e^+} - D^*_{e^-})$ and E, σ_E are the beam energy and spread respectively. (Here the corrections arising from the RF system are ignored.)

As ΔD_y^* is a characteristic of the bunch train bumps and σ_E can not be reduced to zero the only practical control of this effect is to reduce δy as much as possible. In the 1995 energy scan, LEP was operated with 4 trains of 3 wagons per beam (4*3 + 4*3). Under such circumstances it not possible to collide all wagons with zero δy since the residual beam-beam kicks generate transverse distortions of the train [12]. It is shown in [11] that optimization of the total luminosity results in a cancellation of the individual ΔE_{cm} of each collision in the train provided that the difference dispersions are the same for each family (the three collisions in a train will be referred to as families a, b and c).

Common Errors				
Error		ΔE_{CM} (MeV)	P $\pm$ 2 Corr.	Comments
Mean $\langle z \rangle$ shift		0.1	100%	
Wagon $\langle z \rangle$ shifts	IP4, 8	0.4	50%	
	IP2, 6	0.6	50%	
$Q_s(e^-) - Q_s(e^+)$		0.2	50%	IP4 and IP8 anticorr.
Missing data		0.1	50%	

IP-Specific Errors				
Error		ΔE_{CM} (MeV)	P $\pm$ 2 Corr.	Comments
$\Delta \ell_{26}$	IP4, 8	1.0	100%	IP4 and IP8 anticorr.
Voltage scale	IP2	0.4	100%	
	IP6	0.1	100%	IP2 and IP6 corr.
RF misphasing	IP2	0.1	50%	
	IP6	~ 0	-	
RF misalignment	IP2	0.8	100%	
	IP6	1.9	100%	uncorrelated
$\Delta \alpha_c$	IP2	0.1	100%	
	IP6	0.1	100%	IP2 and IP6 corr.

Table 3: *A summary of the systematic errors for the preliminary 1995 analysis of the RF corrections. Those errors common to all experiments are given first, and should be assumed to be 100% correlated IP to IP. The additional errors for the individual IPs and their correlations are given below.*

The strategy for controlling collision offsets [13] was to perform Vernier scans during each offpeak fill (once near the beginning of the fill and once near the end). The luminosity as a function of the beam separation indicates the Vernier setting for maximum luminosity for each family. The average of the three families gives the *optimal* Vernier setting.

Additionally, the opposite sign vertical dispersion must also be measured in order to set the size of the effect. This was also done with Vernier scans. The shift in the optimal Vernier setting when the beam energy is changed is directly proportional to the difference in the vertical dispersion. The LEP beam energy is changed by changing the RF frequency. The difference in the dispersion of the two beams is then given by:

$$\Delta D_y^* = -\frac{\alpha_c \cdot f_{RF}}{\Delta f_{RF}} \cdot \Delta y_{opt} \tag{6}$$

where Δy_{opt} is the observed shift in the optimal Vernier setting when the RF frequency, f_{RF}, is shifted by Δf_{RF}. The momentum compaction factor is denoted by α_c.

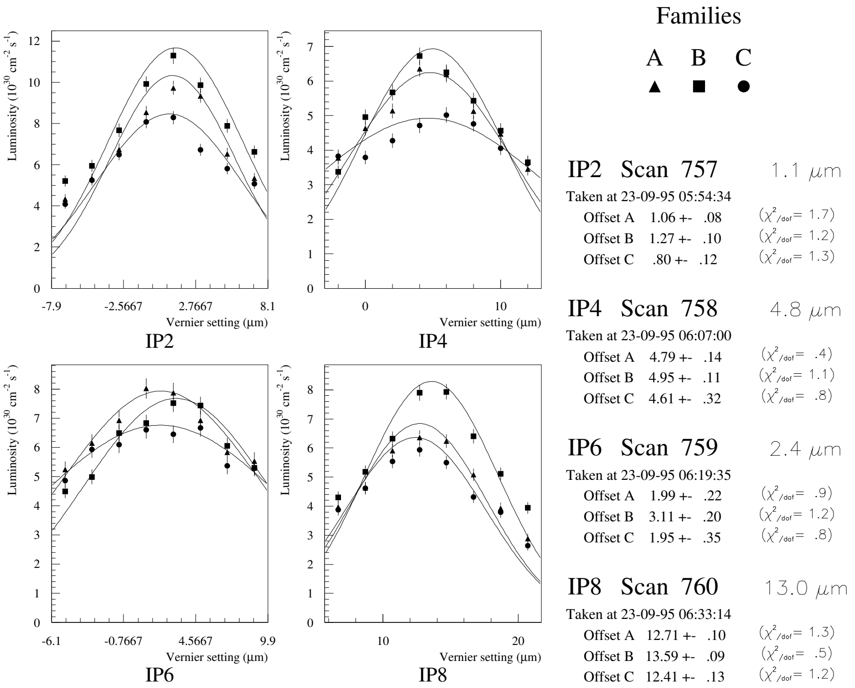


Figure 5: *Typical online display of Vernier scans taken at each IP.*

6.2 Vernier scans

Vernier scans were performed once or twice in a fill. After the scan was completed, a display of the scan would appear and the operator would adjust the Vernier setting to the optimal position given by the online fit result. Figure 5 shows the display of a series of Vernier scans as it appeared in the LEP control room.

The Vernier scan data were re-analyzed offline to study quality, stability and other characteristics of the scans. The gaussian fits were found to be good with a mean χ^2 p.d.f. of $\sim$ 1.2. The typical statistical error on the optimal Vernier position per family is 0.2 - 0.3 μm. There were $\sim$ 35 good Vernier scans taken at each IP and at each offpeak energy for the purposes of controlling collision offsets ($\sim$ 13 on peak).

6.2.1 Stability

The stability of the optimal position is shown in figure 6 for IP2 as a function of time into the 1995 energy scan running period (time since Jan 1, 1995). The RMS variation of the optimal position is $\sim$ 1.0 to 1.5 μm. With $\sim$ 35 Vernier scans at each offpeak point, the mean position is therefore known to an accuracy of $\sim$ 0.2 μm.

6.2.2 Vertical Beam Size

It is known that the vertical size of the beams may change during a Vernier scan. Since the variation of the beam size results in variations of the luminosity, it was possible to use the luminosity of the other IP's during the scan to estimate the changing beam size [14]. This correction reduced the mean χ^2 p.d.f. of the fits from $\sim$ 1.2 to $\sim$ 1.1.

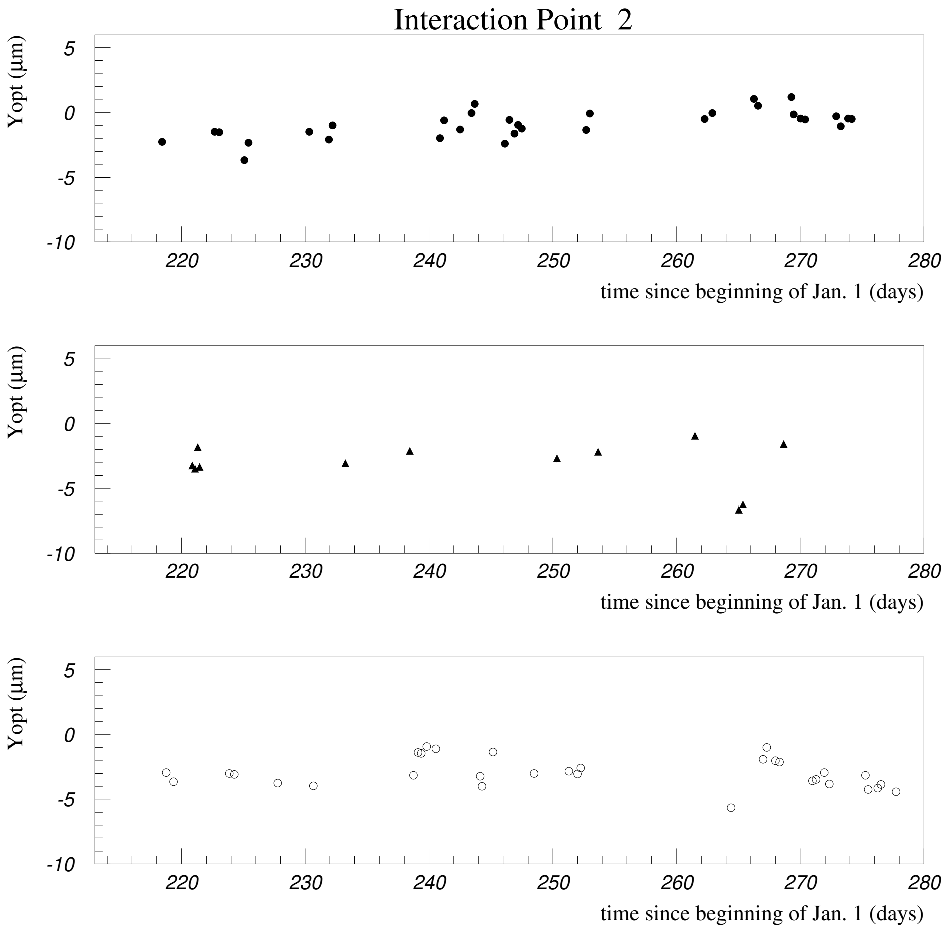


Figure 6: *The stability of the optimal Vernier setting for IP2 during the 1995 energy scan.*

An important quantity to come out of the Vernier scan fits is the vertical beam size itself (σ_y) since the centre-of-mass energy effect is (according to eq. 5) inversely proportional to the square of the beam size. Vertical beam sizes were measured at each IP and offpeak point. They fell in the range of 4 to 5 μm.

6.3 Collision Offsets

In order to calculate the collision offset it is necessary to compare the optimal Vernier setting, y_{opt}, with the *actual* Vernier setting, y_{set}. The collision offset, δy, is defined as:

$$\delta y = y_{set} - y_{opt} \tag{7}$$

The error on the luminosity weighted collision offset, $\delta \langle \delta y \rangle_{lum}$, comes from the error on $\langle y_{opt} \rangle_{lum}$ since it is not known at all times and has a large RMS variation. The collision offsets for each IP and energy point are given in table 4.

Luminosity weighted collision offsets	
IP	mean (μm)
L3 P–2	0.43 $\pm$ 0.17
L3 P	0.24 $\pm$ 0.36
L3 P+2	-0.05 $\pm$ 0.17
ALEPH P–2	0.53 $\pm$ 0.19
ALEPH P	0.11 $\pm$ 0.33
ALEPH P+2	-0.36 $\pm$ 0.19
OPAL P–2	0.34 $\pm$ 0.24
OPAL P	0.17 $\pm$ 0.30
OPAL P+2	0.15 $\pm$ 0.30
DELPHI P–2	0.18 $\pm$ 0.16
DELPHI P	0.57 $\pm$ 0.32
DELPHI P+2	-0.16 $\pm$ 0.24

Table 4: *The luminosity weighted collision offset in μm.*

6.4 Dispersion measurements

The difference dispersion ΔD_y^* is measured by observing the shift Δy_{opt} in the optimal Vernier setting, due to a shift in the beam energy. Beam energy shifts are accomplished by changing the RF frequency and thereby changing the radius of the orbit. The relation between ΔD_y^* and Δy_{opt} is given in equation 6.

Dispersion measurements were made for each IP at each energy. The results were averaged over the energies and yielded ΔD_y^* measurements of $\sim$ 2 mm at each IP.

6.5 Energy shifts

Using the results from the previous sections for mean collision offset, beam size and difference dispersion, the sensitivity to collision offsets for each IP was determined to be -2.3, 1.3, -1.4 and 1.6 MeV/μm for IP 2,4,6 and 8 respectively.

This sensitivity can be combined with the collision offsets given in table 4 to obtain an estimate of the centre-of-mass energy shifts at each IP and energy. This is shown in table 5. The error is due to the statistical error on the collision offset, δy, from table 4.

ΔE_{cm} for each Interaction Point	
IP	$\Delta E_{cm}(MeV)$
L3 P–2	-0.99 $\pm$ 0.39
L3 P	-0.55 $\pm$ 0.83
L3 P+2	0.12 $\pm$ 0.39
ALEPH P–2	0.69 $\pm$ 0.24
ALEPH P	0.14 $\pm$ 0.41
ALEPH P+2	-0.47 $\pm$ 0.24
OPAL P–2	-0.48 $\pm$ 0.33
OPAL P	-0.24 $\pm$ 0.41
OPAL P+2	-0.21 $\pm$ 0.41
DELPHI P–2	0.29 $\pm$ 0.25
DELPHI P	0.91 $\pm$ 0.50
DELPHI P+2	-0.26 $\pm$ 0.38

Table 5: *Estimate of the centre-of-mass energy correction, ΔE_{cm}. The error is due to the error on the determination of the collision offset, δy.*

6.6 Systematic studies

Systematic errors have been evaluated by studying the behaviour of Vernier scans as well as from the errors on the various measuremnts using them.

In addition to the statistical errors quoted in table 5 the following uncorrelated systematic errors have been evaluated:

- The contribution from the error on the measurement of ΔD_y^*.
- The contribution from the assigned error on the vertical beam size. An error has also been assigned to cover the variation due to using a mean beam size or using a time dependent beam size.
- The results from the gaussian fit have been compared to the results of the beam size corrected fit, as well as to those of another fit (and model) which uses the BEUV [15].

- Errors due to differences amongst the families and the train shape.

Systematic errors have been evaluated which are correlated between the different energies and IP's.

- A possible bias resulting from the direction that the Vernier voltages are scanned. This is the result of studies of Vernier scans which were performed in the opposite direction.

- Vernier sampling bias due to drifts during a fill. This behaviour is observed to be similar at P–2 and P+2 at each IP.

The offpeak average of these errors as well as the statistical errors are given in table 6 for each IP.

Errors on ΔE_{cm} (MeV)			
IP	Statistical	Uncorrelated	Correlated
L3	0.39	0.46	0.31
ALEPH	0.24	0.35	0.18
OPAL	0.37	0.34	0.20
DELPHI	0.32	0.36	0.24

Table 6: *Mean statistical errors on ΔE_{cm} for each IP. The systematic errors are labeled uncorrelated and correlated.*

7 Summary of the systematic errors on the 1993, 1994 and 1995 LEP collision energies

7.1 Introduction and formalism

Preliminary systematic errors have been evaluated on the 1993, 1994 and 1995 energies. Note that for 1993 these supersede those given in [1].

The systematic uncertainties have correlations between energy points, between IPs and between years. For the convenience of the LEP electroweak working group a 6×6 matrix was constructed which held the correlations between the P–2, P and P+2 in 1993 and 1995. This matrix contains the errors in common between each IP; thus terms wholly anti-correlated between IPs were excluded, and terms uncorrelated between IPs were represented by a pseudo-common error with the same magnitude as the weighted sum of the uncorrelated errors. This formalism enables the energy errors to be correctly accounted for in the determination of the lineshape parameters of the combined LEP experiments.

The errors on the prescan points of 1993 and 1995 were described with single values, as was that of the peak point in 1994. These uncertainties were significantly larger than those on the scan points, and so the correlations between years could be safely neglected.

7.2 Errors on the energy determination

Here a summary is given of those components in the error assignment which are most significant or new. The other contributions are as discussed in [1].

7.2.1 Uncertainties in the rise term

The knowledge of the energy rise in a fill has associated errors. The uncertainty on the absolute energy rise gives an error on M_Z, whereas the assumption that this rise is the same at P–2 and P+2 is accompanied by a systematic uncertainty which translates into an error on Γ_Z.

The predictions of the NMR model can be compared directly with depolarisation data for the BOF/EOF calibration experiments of 1993 and 1995. The results of these comparisons are summarised in figures 2 and 3. These give a statistical measure of the performance of the model. From this procedure errors of 2 MeV and 1 MeV were assigned to the knowledge of the energy rise in 1993 and 1995 respectively, uncorrelated between the years.

To what degree the rise term has the same magnitude and shape at P–2 and P+2 was quantified from the NMR data. These indicated that the error induced on Γ_Z from this assumption is less than 0.6 MeV. As there were no tunnel NMR data in 1993, this error was taken to be common to the two scans.

As discussed in sections 3.2 and 4, an alternative to the NMR based model is one derived from a fit to the depolarisation data alone. This gave similar results, but differences arose from the variation in behaviour of the models at long fill times. The full difference between the mean energies obtained with each approach was taken as a modelling error, fully correlated between years. This difference is not the same at each energy point and therefore the uncertainty affects both M_Z and Γ_Z.

Small additional modelling errors were assigned to account for the variations observed when different assumptions were used in constructing the NMR based model, in particular different values of the temperature coefficient C_T^{48}.

7.2.2 Correctors

Until the effect of correctors on the beam energy is empirically studied in a dedicated experiment, a systematic error must be assigned to account for the uncertainty. This was done, taking as the scale of the effect that indicated by simulation. For 1995, half of the effect was included in the central values, and half assigned as an error. For 1993, no change had been made to the central value and so the full effect was taken the error. In both years this component induces an uncertainty of approximately 1 MeV on Γ_Z and 0.8 MeV on M_Z.

7.2.3 Mean fill energy

The dominant error in the first analysis of the 1993 data was the knowledge of the mean fill energy: the scatter of the model with respect to the depolarisation measurements can be used to infer the uncertainty in the mean energy at each offpeak point. For 1995 the error from this source on Γ_Z and M_Z is approximately half of that assigned in 1993. This improvement is mainly due to the significantly increased fraction of offpeak luminosity in 1995 which was calibrated.

The estimated error for the 1993 scan was improved by a more complete evaluation with respect to that in [1], to take into account the relative luminosities in the calibrated and uncalibrated fills.

7.2.4 RF and dispersion corrections

The errors associated with IP specific corrections arising from the RF system and opposite sign vertical dispersion have been summarised in sections 5 and 6. These systematics are not dominant; in paticular, those from the dispersion corrections are small, inducing a $\sim$ 0.3 MeV error on M_Z and a $\sim$ 0.25 MeV error on Γ_Z. This indicates the success of the Vernier scan programme in coping with this potentially troublesome source of uncertainty [2].

7.3 Preliminary LEP error matrix

The preliminary error matrix for the 1993 and 1995 scans is shown in table 7.3.

	93 P−2	**93 P**	**93 P+2**	**95 P−2**	**95 P**	**95 P+2**
93 P−2	8.4	4.4	4.3	0.4	0.0	0.0
93 P	4.4	40.0	6.9	0.1	1.7	0.7
93 P+2	4.3	6.9	9.4	0.1	1.4	1.3
95 P−2	0.4	0.1	0.1	2.6	1.4	1.2
95 P	0.0	1.7	1.4	1.4	22.2	2.1
95 P+2	0.0	0.7	1.3	1.2	2.1	5.4

Table 7: *LEP energy common error matrix for the scan points of 1993 and 1995. The values are for collision energy in units of* MeV^2.

The preliminary error assignments for the prescan in 1993 was 18 MeV and for the prescan in 1995 was 30 MeV. That for the former was unchanged from the value given in [1] – the new uncertainties are negligible alongside this error. The 1995 prescan error is large because of the very preliminary nature of the analysis, accentuated by the poor logging of LEP parameters in this period.

The preliminary error assignment for the peak point in 1994 was 4.5 MeV. This is composed of the previously used preliminary error [2], with an additional component of 2 MeV to account for uncertainties in the rise term.

8 Energy spread in 1993, 1994 and 1995

The beam energy spread $\sigma_{E_{beam}}$ is related to the observed longitudinal size of the interaction region σ_z through the following formula :

[2]Indeed, this potentially dominant systematic error had called into question the feasibility of the 1995 scan.

$$\sigma_{E_{beam}} = \frac{\sqrt{2}E_{beam}}{\alpha_c R_{\text{LEP}}} \times Q_s \times \sigma_z \tag{8}$$

where E_{beam} is the beam energy, α_c is the LEP momentum compaction factor, R_{LEP} is the LEP bending radius, Q_s is the synchrotron tune and σ_z the RMS of the longitudinal event vertex distribution observed in an experiment (in this analysis, ALEPH).

The centre-of-mass energy spread $\sigma_{E_{CM}}$ is related to the beam energy spread $\sigma_{E_{beam}}$ by the simple formula: $\sigma_{E_{CM}} = \sqrt{2} \times \sigma_{E_{beam}} \times C$, $(0 \leq C \leq 1)$. For colliding beams having no or identical energy dispersions (as in 1993 and 1994) the *monochromatization* factor C is approximately equal to 1 [11]. This is not the case for data taken in 1995 with bunch train operation mode.

The main uncertainty on $\sigma_{E_{beam}}$ comes from the definition of Q_s. Equation 8 is written in terms of the incoherent $Q_s^{\text{inc.}}$, e.g. that of individual particles. Collective effects modify the Q_s value. Only the coherent value $Q_s^{\text{coh.}}$ is measured regularly.

A determination of $Q_s^{\text{inc.}}$ was obtained by accurate determination of the Q_s side band of the depolarizing resonance during an energy calibration. The experiment was carried out on 2 September 1995. Parameterising the relation between $Q_s^{\text{coh.}}$ and $Q_s^{\text{inc.}}$ as $\frac{Q_s^{\text{coh.}}}{Q_s^{\text{inc.}}} = 1 - \kappa\frac{I}{I_0}$ (where I is the bunch current), the measurement yielded $\kappa = 0.044 \pm 0.022$, for $I_0 = 300\ \mu$A.

This value of κ was used to compare the 1995 beam energy spread as determined through expression 8 to a model based on the energy loss around the ring [17]. Data and model agreed for κ values consistent with that measured. Consequently, the same value of κ was used to evaluate the beam energy spread for 1993 and 1994.

In the presence of opposite sign energy dispersion between electrons and positrons, the LEP centre-of-mass energy spread $\sigma_{E_{CM}}$ can be less than $\sqrt{2} \times \sigma_{E_{beam}}$ [11]. The energy dispersion for the 1993 and 1994 pretzel running has been evaluated [18]. The reduction on the centre-of-mass energy spread is estimated to be less than 0.2%. This corresponds to a change of only 0.1 MeV on $\sigma_{E_{CM}}$ and is therefore neglected. The dispersion in 1995 is larger, due to the bunch train bumps, and leads to a significant monochromatization. This gives a correction of $\sim 2\%$, with an IP dependence [10].

The LEP centre-of-mass energy spread is given in table 8 for the different years of running and for the different energy points. For 1993 and 1994, the error on the spread (dominated by the uncertainty on κ) is 1.1 MeV. For 1995 this error is increased to 1.3 MeV due to beam dispersion. These numbers are fully correlated between years and experiments. They represent a fourfold increase in precision on previous evaluations.

	93	94	95			
			IP2	IP4	IP6	IP8
P–2	54.6		55.0	55.7	55.7	55.7
P	55.4	54.9	55.6	56.2	56.2	56.3
P+2	55.6		56.0	56.6	56.7	56.7

Table 8: *Centre-of-mass energy spread in* MeV

LEP centre-of-mass energy variations increase the apparent energy spread. The RMS of the LEP centre-of-mass energy distribution for each year and each energy point has to be added in quadrature to the number given in table 8. In previous analyses this term has been neglected as small compared to the error.

9 Summary and outlook

The prelimary analysis of the 1995 LEP scan already allows the collision energy to be determined with good precision. Of particular importance in the analysis is the modelling of the energy rise in a fill. It is possible that understanding of the energy rise will improve as a result of future data. These data will come from the ongoing testbench studies of a LEP dipole and from additional calibration experiments and NMR measurments in the present run. The latter will be particularly interesting as in addition to the 2 NMRs of 1995, 14 new devices have been installed. As well as having consequences for the 1995 analysis, any improvement in understanding will be particularly useful in the revision of the 1993 energies.

An additional uncertainty, present in both the 1993 and 1995 analyses, is the effect of the corrector magnets on the beam energy. Dedicated experiments scheduled for the present run will show whether this effect is as predicted by simulation.

The analysis of the IP specific corrections in 1995 give preliminary errors which are not large. The Vernier scans were a very successful tool in minimising the potentially large energy shifts arising from the bunch train induced vertical beam dispersion. More work is needed to fully understand the interaction of the bunch trains and the RF system.

A new analysis of the beam energy spread has improved the precision to the extent that it now contributes negligible error to Γ_Z.

References

[1] The working group on LEP energy, R. Assman et al., Z. Phys. **C66** (1995) 567.

[2] M. Koratzinos, contribution to the 64th LEP Energy WG meeting (Feb 17, 1995).

[3] L. Arnaudon et al.,Phys. Lett. B284 (1992) 431.
L. Arnaudon et al., 'The Energy Calibration of LEP in 1991', CERN-PPE/92-125
The Working Group on LEP Energy and the LEP Collaborations, Phys. Lett. B307 (1993) 187.

[4] G. Brun et al.,'A Newly Observed Effect Affects the LEP Beam Energy', 5th European Particle Accelerator Conference - EPAC '96, Sitges, Spain / 10 - 14 Jun 1996.

[5] M. Geitz, 'Investigation of the Environmental Effects on the LEP Beam Energy', diploma thesis, RWTH Aachen, PITHA Nr.96/14, also to be published as CERN SL/96-xx (BI).

[6] M. Koratzinos, 'The Energy of LEP in the 1995 Scan - Dipole Model', LEP Energy Group/96-03.

[7] P. Renton, G. Wilkinson and K. Yip, 'Studies of the LEP Energies in the 1993 and 1995 Scans', LEP Energy Group/96-04.

[8] E. Bravin and B. Dehning, private communication.

[9] M.D. Hildreth, G. Duckeck, G. Quast, G. Wilkinson, K. Yip, 'Preliminary RF Corrections to the LEP Energy for the 1995 Scan', LEP Energy Group/96-02.

[10] P. Puzo, J. Yamartino, 'Preliminary Centre-of-Mass Energy Corrections from Dispersion and Collision Offsets for the 1995 Scan', LEP Energy Group/96-01.

[11] J.M. Jowett, J. Wenninger, J. Yamartino, 'Influence of Dispersion and Collision offsets on the Centre-of-Mass Energy at LEP', CERN-SL/note 95-46(OP).

[12] E. Keil, 'Truly Self-Consistent Treatment of the Side Effects with Bunch Trains', CERN SL/95-75.

[13] The LEP Energy Working Group, 'LEP Centre-of-Mass Energies in Presence of Opposite Sign Vertical Dispersion in Bunch train Operation', LEP Energy Group/95-2.

[14] P. Puzo, contribution to the 81st LEP Energy WG meeting (Oct 26, 1995).

[15] M. Koratzinos, contribution to the 78th LEP Energy WG meeting (Sep 21, 1995).

[16] Detailed note in preparation by E. Lançon and A. Blondel.

[17] J.M. Jowett, private communication.

[18] J.Wenninger, 'Centre-of-Mass Energy shifts from Difference Dispersion and Collisions Offsets in Pretzel Operation at LEP', CERN-SL/note 95-64(OP).